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FIELD STUDIES OF LINER INSTALLATION METHODS AT LANDFILLS AND SURFACE IMPOUNDMENTS

by

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Grant No. R806645010

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Objectives of the study were to identify liner installation practices recommended by industry, to identify methods and equipment used for subgrade preparation and liner installation, and to compare industry recommended procedures with actual practice. The study also identifies special problems that can be avoided by following proper placement procedures. Emphasis is given to polymeric membrane liners because most liners currently being installed are of that type.

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ABBREVIATIONS

HDPE	High density polyethylene
EPDM	Ethylene propylene diene monomer
CSPE	Chlorosulfonated polyethylene
PVC	Polyvinyl chloride
CPE	Chlorinated polyehtylene
QA/QC	Quality assurance/quality control
UV	Ultraviolet

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SECTION 1

INTRODUCTION

The use of surface impoundments and landfills to store, treat and/or dispose of unwanted materials has been and continues to be common practice for industry and municipal agencies since these types of facilities have proven to be cost-effective solutions to treatment and disposal problems. Recent studies have shown that the use of such facilities can result in subsurface migration of hazardous materials into ground-water resources.

The Resource Conservation and Recovery Act of 1976 and proposed U.S. Environmental Protection Agency (EPA) regulations require prevention of subsurface migration of contamination from those facilities where hazardous materials are stored. Natural and manmade liners are currently being used to prevent or minimize seepage of polluting fluids from surface impoundments and landfills. Numerous types of liners exist. Liners most often used in disposal facilities are classified by type of construction, structure, materials, and method of application (Table 1). These liners prevent or minimize fluid seepage in two ways. Either they physically impede the flow of fluid; or they absorb or retain contaminating, unwanted chemicals in the fluid. Soils generally absorb certain contaminants and will also impede the flow of fluid because of low permeability. Manmade liners function more as a barrier to fluid flow as a result of very low permeability.

This study was initiated in 1979 to investigate liner placement procedures and subgrade preparation during the construction of lined fluid surface impoundments and landfills for fluids. The purpose of lining such facilities is to reduce the risk that polluting fluids will migrate from the site and contaminate surface or ground-water resources.

The proper planning, design, and construction of lined containment facilities involve numerous steps, including the following:

(1) Defining facility function and geometry;

(2) Selecting a liner type that is compatible with the substances to be stored or treated;

(3) Planning suitable subgrade preparation, seepage monitoring, and collection systems (if appropriate);

(4) Planning proper liner installation; and

TABLE 1. CLASSIFICATION OF LINERS FOR WASTE DISPOSAL FACILITIES*

Method of Classification	Type of Liner
Construction:	
Onsite	Raw materials bought to site and liner constructed there Compacted soils Mixed on site or brought to site mixed Sprayed-on liner
Prefabricated	Drop-in polymeric membrane liner
Partially prefabricated	Panels brought to site and assembled or prepared there
Structure:	
Rigid	Soil Soil cement
Semirigid	Asphalt concrete
Flexible (no structural strength)	Polymeric membranes Sprayed-on membranes
Material and method of application	Compacted soils and clays Admixes (e.g., asphalt concrete, soil cement) Polymeric membranes (e.g., rubber and plastic sheetings) Sprayed-on linings Soil sealants

*Source: Matrecon, Inc.

(5) Developing appropriate post-installation operation, maintenance, and closure plans.

This study addresses subgrade preparation techniques and placement procedures for a variety of liner materials. The lining materials included are admixes, soils and clays, sprayed-on membranes, and polymeric membranes. The objectives of the study were:

(1) To identify suggested liner installation practices within the industry,

(2) To identify the methods and equipment used for subgrade preparation whenever possible,

(3) To identify methods and materials used to install liners,

(4) To compare suggested procedures with actual practice, and

(5) To identify special problems that can be avoided by following proper placement procedures.

The conclusions and recommendations based upon this study are presented in Sections 2 and 3, respectively. Section 4 presents the approach used to accomplish the study objectives, and Section 5 presents the results and discussion. A detailed discussion of the liner industry is not presented in this report. The reader is referred to EPA Report SW-870, Lining of Waste Impoundment and Disposal Facilities.

SECTION 2

CONCLUSIONS

Field observations at 21 liner construction sites indicate that installers generally complied with industry suggestions regarding subgrade preparation and liner placement procedures. Two important aspects for which there are no consistent suggestions or definitions within the flexible liner industry are quality control inspection procedures and field seam testing requirements. Several manufacturers and installers of polymeric membrane liners are developing and implementing methods to test the quality of field seams. Increasing owner awareness of the importance of quality control procedures during construction should be encouraged and will help develop this practice within the liner industry.

Though the liner industry literature suggests procedures for installation, these must often be modified to accommodate special site problems or characteristics. Accommodation that ensures reliable construction and installation methods requires an experienced, knowledgeable installation crew that can adapt to various field situations. At present, the final responsibility for liner system performance rests with the owner, who would be well advised to take an active part in the planning, installation and operation of a lined surface impoundment or landfill. No particular liner installation technique or procedure guarantees a successful liner system. Facts about the impact of installation procedures on successful systems are not available to the entire technical community involved in liner system design, construction, and operation. Factual, unbiased data are needed to improve the overall quality and reliability of liner systems. A series of nationally accepted guidelines defining methods and procedures for the installation of various materials would be useful. Included in these guidelines should be a well-defined, meaningful quality assurance program that can be implemented by a prospective owner to ensure effective field installation procedures.

SECTION 3

RECOMMENDATIONS

Research is needed to determine the impact of installation procedures and subgrade conditions on liner system performance. This information would verify that the desirable or commonly used practices actually do produce liner systems that perform as intended. One approach to achieving this goal would be to track the performance of the liner systems at the sites visited during this project.

A final recommendation is for research to develop methods to test the quality of field seams for membrane liner systems. Field seams are critical to the success of the liner system. Testing of all seams would demonstrate liner system integrity. The most desirable method would be nondestructive to the liner. This would allow all seams to be tested. The method would also need to be field-operational.

SECTION 4

RESEARCH APPROACH

IDENTIFYING INDUSTRY SUGGESTED PRACTICES

Liner installation procedures and desirable subgrade characteristics suggested by the industry were identified through personal contacts with industry representatives, and review of the current industry literature. Industry representatives included designers, manufacturers, fabricators, and installers of the membrane liners and soil sealants.

Suggested practices for five generic types of liners were identified. The five liner types were:

(1) Polymeric membranes
(2) Compacted clays
(3) Field constructed membranes (sprayed on)
(4) Soil sealants
(5) Admixes

Suggested practices were solicited for those installation procedures and subgrade characteristics listed in Table 2. These procedures and characteristics were considered important by industry representatives contacted during the initial phase of the study.

SELECTING SITES TO VISIT

During phone conversations with industry representatives, information was also obtained regarding upcoming construction activities. A master list of liner installation sites was developed. Details about each location were obtained either from the installer/contractor, design engineer, or the facility owner. The specific data required for each site are listed in Table 3. Considerations used to determine which sites to visit are as follows:

Liner type (membrane, clay, soil sealant, etc.)
Facility type (landfill, surface impoundment, etc.)
Construction schedule
Permission to take photographs
Experience of installation crew
Size of facility

TABLE 2. INSTALLATION PROCEDURES AND SUBGRADE CHARACTERISTICS

Installation Procedures	Subgrade Characteristics
Site Storage of Material	Surface Texture
Equipment Used to Place Liner	Compaction Required
Technique of Positioning Liner	Herbicide Treatment
Material Overlap	Surface Geometry
Field Seaming Technique	Surface Composition
Adhesives Used	
Tools Required	
Weather Limitations	
Crew Size and Experience	
Sealing Around Penetrations	
Anchoring System	
Soil Cover Details	
Quality Control Program	
Application Rates for Soil Sealants	
Clay Composition	
Support Fabric Used	

Sites were eliminated from consideration if photographs were not allowed and if the construction schedule did not coincide with the project schedule. Establishing visitation schedules required coordination with the site owner, liner installer, and design engineer for most sites. Every effort was made to locate construction sites representative of the five generic liner types included in the project plan. Whenever possible, site visits were scheduled when both subgrade preparation and liner installation were in progress.

Before each site visit, an installation summary was prepared detailing the industry-recommended installation practices, the desirable subgrade characteristics, and the anticipated activities based upon discussions with the installation contractor, owner, and design engineer. This analysis served as a basis for comparing expected and observed practice.

DOCUMENTING FIELD INSTALLATION PROCEDURES

Field installation procedures and subgrade characteristics were observed at 21 facilities, as listed in Table 4. Observations were documented with photographs and field notes. Onsite activities were discussed with the person in charge to clarify the rationale for observed installation and subgrade construction methods. Every effort was made to remain at the site long enough to observe all aspects of liner installation procedures. In most cases, both installation and subgrade construction procedures were observed while on site, since the jobs were large enough that these activities were going on concurrently. But for several sites, only liner installation procedures could be observed, as subgrade construction had been completed. Field placement procedures and subgrade construction activities were compared with suggested practices during the site visit. Comments from field personnel regarding the reasons for observed field activities were solicited by the field crew.

TABLE 3. SITE DATA REQUIREMENTS

Item	Data required
General Information:	Site name
	Location
	Date of visit
	Type of facility
	Liner material
	Manufacturer
	Fabricator
	Installer
	Designer
	Site geometry, topography
	Waste to be stored
	Climate
	Weather conditions
Subgrade Preparation:	Subgrade type
	Compaction methods
	Grading
	Equipment used
	Special treatment
	Surface texture
	Penetrations
	Slide slopes
	Geotextile used
	Seepage monitoring
	Seepage collection
Liner Placement:	Site storage of material
	Positioning sheeting
	Equipment used to place liner
	Seam overlap
	Field seaming technique
	Adhesive used
	Tools required
	Crew size and experience
	Sealing around penetration
	Anchoring system
	Soil cover details
	Quality assurance program

SECTION 5

RESULTS AND DISCUSSION

The following sections describe industry suggested installation practices, the field observations made during visits to the 21 liner installation projects listed in Table 4, and a comparison of suggested and observed practices. Subgrade considerations are discussed wherever data are available.

TABLE 4. FACILITY AND LINER TYPES STUDIED

Facility Type	Liner Type
Tailings Storage	Polymeric Membrane
Municipal Landfill	Polymeric Membrane
Evaporation Pond	Sprayed-on Membrane
Potable Water Storage	Polymeric Membrane
Municipal/Industrial Wastewater	Soil Sealant
Geothermal Brine Storage	Polymeric Membrane
Municipal Landfill	Asphaltic Concrete
Evaporation Pond	Polymeric Membrane
Tailings Storage	Polymeric Membrane
Potable Water Storage	Soil Sealant
Evaporation Pond	Recompacted Clay
Municipal Landfill	Soil Sealant
Potable Water Storage	Polymeric Membrane
Evaporation Pond	Polymeric Membrane
Hazardous Materials Landfill	Clay/Polymeric Membrane
Naphtha Spill Containment	Polymeric Membrane
Industrial Wastewater Storage	Polymeric Membrane
Municipal Landfill Cover	Polymeric Membrane
Municipal Wastewater Storage	Polymeric Membrane
Cooling Tower Blowdown Treatment	Soil Sealant
Fuel Oil Spill Containment	Polymeric Membrane

The following subsection is based on a summary of available industry suggestions obtained during the project. In addition, emphasis is placed on polymeric membrane liners because most liner systems presently being installed are membranes.

INDUSTRY SUGGESTED PRACTICES

Liner installation practices suggested by the industry are presented in the following discussion for five generic types of liners: (1) polymeric membrane materials, (2) compacted clay, (3) sprayed-on membrane materials, (4) soil sealants, and (5) admix material (asphaltic concrete).

Membrane Liners

The installation of flexible membrane liners requires proper planning before construction. Important elements of installation are adequate subgrade, onsite storage of materials, installation equipment, manpower requirements, procedures for liner placement, field seaming procedures, sealing around structures or penetrations, quality assurance/quality control procedures and soil cover requirements. Each of these elements is discussed below.

Subgrade Considerations--

General industry suggestions are very similar regarding subgrade characteristics. For an earthen structure, the subgrade must be firm and dry, free of all rocks, roots, debris, or other objects that might tear or puncture the liner. Backfilling is recommended if necessary to meet these conditions. Where vegetation has been cleared to prepare the site, or soil has been brought in to provide a bed for the liner, soil sterilization is specified to prevent grasses from growing through the liner. This is especially true in areas where prior growths of nut or quack grasses have existed. Areas where excavated soil is deposited to create subgrade may also require sterilization.

Compaction--Compaction of the subgrade is normally specified to provide a firm support for all membrane lining materials. Generally, a fill subgrade is built up in a series of compacted layers, whereas an excavated subgrade is compacted only at the surface. Usually, the minimum compaction of the subgrade material will be specified. Most liner installations specify that the density of the subgrade be at least a specified percentage of that obtainable by the Standard Proctor Test, ASTM D698, with 90 percent of Proctor being the most frequently specified relative compaction. Some contracts will specify the compaction equipment which is to be utilized, number of equipment passes per layer, layer thickness, permissible water content range at placement, and method and location of water addition.

The regularity and texture of the surface of the uppermost layer is critical to a successful liner installation. A plane surface after compaction is the most desirable one for liner placement but is not always achievable or specified in the contract. In many installations, soil clods or local surface irregularities will be flattened (further compacted) by the overlying weight of the stored material after the facility is filled. Further, it is thought that the polymeric membrane liners will adjust their shape over any clods so that no detrimental effects will result. Nevertheless, rocks or irregularities with sharp edges should be eliminated from the finished subgrade during the compaction/construction process even when not specified in the contract if liner integrity is to be maintained.

Within the polymeric membrane liner industry, there is a difference of opinion as to how smooth surfaces must be to maximize liner integrity. The opinions vary with the liner material. It is generally agreed, however, that the smoother the finished surface, the chance of liner failure due to subgrade inadequacies is reduced.

Fine Finishing of Surface--If compaction has been accomplished with a sheepsfoot compactor, it is normal to fine finish the surface. Fine finishing is an intensive aspect of subgrade preparation. Depending on the design specifications, various techniques are recommended. A smooth surface on the bottom and sidewalls can be accomplished with various drags which aid in the formation of a regular, flat working surface. Fine finishing with vibrating rollers and drags is recommended on a slightly wet surface; thus, water tank trucks may be required during the fine finishing activities. Occasionally, soil additions are required to bridge surface irregularities if the irregularities cannot otherwise be removed. Sand is useful for this purpose as it is easily compacted.

The fine finishing process is critically dependent on the proper care and control of water. If rain occurs during or immediately after the fine finishing work on a slope, rills, ruts, ravines, etc., may be eroded into the surface. Thus, the expenditure of efforts to fine finish slopes and bottoms for subsequent membrane liner placement is not recommended when rainfall is imminent; conversely, the placement of liner material on fine finished slopes is recommended as soon after completion of "finishing" as possible to ensure that no surfaces are "lost" to the erosive effects of surface runoff.

Membrane liners are often installed over non-earthen subgrades, such as concrete. In such cases, it is recommended that a soil fill (such as sand), or a geotechnical fabric (geotextile), be placed over the concrete after uneven joints have been filled and smoothed.

On-site Storage of Material--

Membrane materials are normally shipped to a construction site, and must be stored prior to placement. Most materials are folded and shipped on wooden pallets or in rolls. Protection of the liner materials from the effects of heat and from vandalism is recommended. These are the two most important storage considerations. Excessive heating can degrade the surface of the material, causing problems with field bonding. Covering the material with white plastic or storage out of direct sunlight is recommended for all materials. If the material is shipped in cardboard boxes, plastic shielding is not required. Placing the material in a secure area is recommended to prevent vandalism.

Installation Equipment--

Equipment often required to install a membrane liner includes a fork lift truck, backhoe, or front end loader for material placement and various tools necessary for material positioning and field seaming. A fork lift truck, with large rubber tires (not warehouse type), is most often recommended for material placement, because most material is shipped to a site on wooden pallets. The pallets can easily be maneuvered with a fork lift truck.

The equipment needed to seam the material together is basically similar for all types of material, with the exception of high density polyethylene. Table 5 lists the equipment recommended by the industry. High density polyethylene is welded together and requires special equipment.

Manpower Requirements--

Manpower requirements for the installation of liner materials is a function of the rate that the installer wants to place panels and accomplish field seaming. Typically, installation contractors will recommend five to ten people on site when placing one panel at a time. Generally, a crew foreman will direct the activities of the field crew. He may not directly participate in the unrolling and positioning of panels or in field seaming. However, it is recommended that he be experienced in the installation of the specific liner material.

Crew size recommendations also depend on the complexity of the installation and the experience of the field crew. If the majority of the crew members are recruited locally, more members may be needed due to lack of experience. At the present time, the trend is toward having installation contractors retain field supervisors who travel from job site to job site. Large jobs where crews perform specific tasks may involve many people.

Liner Placement--

Important considerations that should be followed in placing a membrane liner are as follows:

(1) Follow manufacturers' recommended procedures for adhesive system, seam overlap, and sealing to concrete.

(2) Use a qualified installation contractor having experience with membrane liner installation, preferably the generic type of liner being installed.

(3) Plan and implement a quality control program which will help ensure that the liner meets specification and the job is installed per specifications.

(4) Document inspection for review and recordkeeping.

(5) Conduct installation during dry, moderately warm weather (above 45°-60°F depending on material).

(6) Subgrade should be firm, flat, and free of sharp rocks or debris.

Before moving panels from the storage site to the installation location, a number of tasks must be performed. The anchor trench around the perimeter of the installation should be completed. The dirt excavated from the anchor trench should be raked smooth so that the panels can be unrolled along and parallel to the anchor trench in the width direction. Other things that must be accomplished prior to panel positioning are: (1) the subgrade should be raked smooth or compacted if necessary; (2) there should be no standing water in the impoundment; (3) any concrete structures that must be seamed

TABLE 5. EQUIPMENT AND MATERIALS FOR INSTALLATION OF FLEXIBLE MEMBRANE LINERS

Item	Use
Fork lift truck	To move liner panels into position.
Backhoe	To backfill anchor trenches.
Tires, sandbags	To anchor unseamed panels to prevent wind damage.
Proper adhesives	To make field seams and seal liner around concrete or steel penetrations.
Portable electric generator	To operate heat guns or lighting for working at night.
Air lance	Quality control testing of field seams.
Hand-held earth tampers and rakes	To smooth and compact subgrade as necessary.
Ladders	For access to side walls/steep slopes.
Miscellaneous materials:	For field seaming.
	- Adhesive applicators (paint brushes, caulking guns, rollers, etc.). - Liner preparation equipment: clean rags, scrub brushes, scouring pads, pails for solvent, hard surface rollers, seaming support board, heat guns, crayons for marking, dowels for pulling panels, stakes and chalk line, steel measuring tape, scissors and utility knives, electrical extension cords (for heat guns).
Field crew equipment:	For field crew when making seams.
	- Safety goggles, solvent resistant gloves, knee pads, respirators, soft soled shoes.
Portable tent/shed	To allow seaming activities in colder/windy weather.
First aid kit	In case of accidents.
Air compressor	Supply air that might be needed when working with solvents, and for air lance.

around should be prepared prior to unrolling any panels; (4) if skirts are to be used around footings on concrete structures, these must be in place prior to the beginning of panel placement; and (5) any outflow or inflow structures or other appurtenances should be in place.

Placement often begins with the unfolding or rolling of the panels in a lengthwise direction. The panels are then unfolded in the width direction, either down the side slope or across the floor. The panels are normally unrolled on the inside of the anchor trench, eliminating the need to move the liner across the trench. The field crew then begins to position or "spot" the panel into its proper location according to the installation plan. As panels are spotted, sand bags are placed along the edges to prevent uplift and subsequent wind damage. The instructions on the boxes containing the liner must be followed to ensure that the panels are unrolled in the proper direction with the correct side exposed for seaming. The panels should be pulled relatively smooth over the subgrade. If the subgrade is smooth and compacted, then the liner should be relatively flat on the subgrade. However, sufficient slack must be left in the material to accommodate any possible shrinkage due to temperature changes. The amount of slack required depends on the material being installed.

Field Seaming--

The panels should be unfolded and spotted so that a sufficient seam overlap of the adjacent panel is maintained. Some materials, such as HDPE, must be allowed time to relax prior to seaming. Seam overlap recommendations vary with liner manufacturer and liner type. Recommended overlaps vary from 4 to 12 inches.

Field seaming is a critical factor in flexible membrane liner placement. Liner manufacturers publish recommended procedures and adhesive systems for achieving successful field seams. Generally, one of four methods is recommended to seam materials in the field. These are a bodied solvent, heat, contact adhesive or adhesive tape. Solvent and contact adhesive systems are the most prevalent. The installation contractor should use the manufacturer's recommended procedure. In some instances, an installer may have worked with a manufacturer to develop an improved technique that works for that installer. In such a case, the method should be allowed.

The integrity of the field seam is determined by many factors. The most important factor is that the adhesive system used must be compatible with the liner material and suitable for use under actual field conditions. As previously indicated, liner manufacturers have specified adhesive systems that work best for their products. These systems normally have limitations with regard to temperature. Generally, manufacturers recommend temperatures above 45°-60°F depending on the material. If ambient temperatures are below this range, manufacturers suggest installation activity cease.

Another important factor in field seam integrity is that the surfaces to be seamed are clean and dry when the field seams are made. The presence of any moisture can interfere with the curing and bonding characteristics of the adhesive used. The presence of any dirt or foreign material can

jeopardize seam strength and provide a path for fluid to migrate through the seam.

Since pressure must be applied to a seam after the adhesive has been applied, it is recommended that the liner ideally should rest on a dry, hard flat surface for rolling. Installers recommend a board or other suitable hard surface be placed underneath the overlap of the liner material. Overlaps can be anywhere from 4 to 12 inches wide, depending on the type of material and the conditions under which seaming takes place. Once the board is placed underneath the liner and the overlap is sufficient, then the top liner material should be peeled back and the surface prepared for the adhesive. In the case of some liner materials, e.g., EPDM and CSPE, a surface cure must be removed with a solvent wash prior to seaming. Field crews should have suitable gloves to prevent skin reactions from the solvents. Respirators and eye protection are also recommended. Once the surface cure has been removed, the adhesive can be applied to the liner material. Generally, with a bodied solvent adhesive, it is recommended that the two surfaces be placed together immediately and rolled with a steel or plastic roller perpendicular to the edge of the panel. Contact adhesive systems require that a certain tackiness be achieved before the two surfaces are placed together.

The crew should be careful not to allow any wrinkles to occur in the seam. All surfaces should be flat and rolled. It is important, whatever adhesive system is used, that the adhesive be applied uniformly. Most installers recommend that field seaming normally begin at the center of a panel and continue to each end of the seam. This minimizes large wrinkles which could occur if seaming began at one end or the other. In all cases, the adhesive system to be used by the field seaming crew should be that recommended by the manufacturer or a suitable substitute approved for a specific job.

Generally, panels are placed so that field seams will run perpendicular to the toe of the slopes; that is, the seams will run up and down rather than along the side slopes. Perpendicular seams are recommended when side slopes are 4 to 1 or greater in slope. The reinforced materials can be placed so that seams run horizontally on side slopes less than 4 to 1. However, perpendicular seams on side slopes are most often recommended for all cases. This practice minimizes stress on uncured field seams. Corner panels are cut to fit as required, usually pie-shaped from berm to the bottom of the facility.

Installation of liner materials and field seaming during adverse weather conditions require special considerations with respect to adhesive systems and temperature limitations. This is particularly true with the thermoplastic materials, since their properties change with temperature. Temperature also affects the rate that solvents will evaporate and the rate that seams become strong. Most manufacturers suggest that their adhesive systems work best when the temperature of the liner material itself is above 60°F. When ambient temperatures are below 60°F and a solvent adhesive system is being used, heat guns can provide an effective means to help bring the temperature of the liner material up to ideal conditions. Extreme caution must be

exercised when using heat guns around flammable solvents, which may ignite, and chlorinated solvents which may generate the toxic gas, phosgene.

Cold weather seaming requires that the field crew exercise caution when making seams to assure that the temperature of the liner material reaches minimum acceptable conditions. A cold weather contact adhesive is sometimes used. Field seaming during precipitation should be avoided.

Depending upon the location and the weather conditions, the number of panels placed in one day should not exceed the number which can be seamed in one day. This assures that, should bad weather conditions occur overnight, unseamed panels will not be left on the subgrade, subject to damage, especially from wind.

Anchoring/Sealing Around Structures/Penetrations--

Proper anchoring of the liner around the impoundment perimeter, as well as conscientious tailoring and sealing of the liner around penetrating structures, are essential to satisfactory liner performance. Generally, in cut-and-fill type impoundments, it is recommended that the liner material be anchored at the top of the dike or berm one of two ways: (1) using the trench-and-backfill method, or (2) anchoring to a concrete structure. The trench-and-backfill method seems to be recommended most often by liner manufacturers, probably due to its simplicity and economy. Excavation of the anchor trench in preparation for laying the liner is usually accomplished with a trenching machine or by using the blade of a motor grader tilted at an angle. The latter method is considered to be less desirable. Dirt from the excavation should be spread away from the pit and smoothed to facilitate unrolling and spotting of panels.

Before opening and spotting the panels, provisions should be made for temporarily securing the edges of the liner panels in the anchor trench while the seaming takes place. After the seaming crew has completed the seams for a particular panel, the trench is backfilled with earth that was excavated from the trench. The trench should not be backfilled until after the panels have been seamed so that panels can be positioned for optimum seaming. If the trench (and the edge of the liner) is to be capped with concrete curbing, it is recommended to position reinforcing rods vertically in the trench prior to backfilling. These reinforcing rods serve to hold the liner in place while the seaming is done.

The perimeter of the liner may also be anchored to a concrete structure along the top of the berm or dike. This is usually accomplished with anchor bolts embedded in the concrete and batten strips composed of a material resistant to attack by the chemical(s) to be stored in the impoundment. Concrete that is to come into contact with the liner should have rounded edges and be smooth and free of all curing compounds to minimize abrasion and chemical interaction with the liner material. Anchor bolts should be positioned not more than 12 inches apart on centers. Concrete adhesive is applied in a strip (minimum width 3-6 inches, depending on the liner material) between the liner and the concrete where the batten strips will compress the liner to the concrete. A strip of lining material (chafer strip) may be sandwiched between the liner and the concrete wherever the liner material

contacts an angle in the concrete structure to prevent abrasion. The batten strips are positioned over the liner material and secured with washers and nuts to the anchor bolts. Mastic should be used to effect a seal around the edge of the liner material. Several alternative methods for anchoring to concrete structures are shown in Kays (1977).

Depending on the design and purpose of the impoundment, one or more types of structures may penetrate the liner. These penetrations could include inlet, outlet, overflow or mud drain pipes; gas vents; level indicating devices; emergency spill systems; pipe supports; or aeration systems. Penetrations may occur in the bottom or through one of the sidewalls, depending upon their function. Because tailoring and sealing the liner around structures can be difficult and offers a possibility for failure of the liner, several manufacturers recommend that over-the-liner pipe placement be used wherever possible. This design facilitates future repairs or maintenance to the piping system.

When penetrations through the liner are necessary, most manufacturers recommend specific materials and procedures to be used to establish an effective seal around the various types of penetrations. Proper design of the penetrations and selection of an adhesive material that is compatible with the liner are important factors to be considered relative to expected liner performance. For instance, some liner materials are not easily sealed to concrete. Selection of alternative materials may be required. Other materials, on the other hand, may offer optimal conditions for obtaining a good seal; for example, PVC liner can be effectively sealed to PVC pipe using the appropriate solvent to bond the materials together.

Most manufacturers offer standardized engineering designs for: (1) seals made in the plane of the liner, and (2) boots to be used around penetrations. If inlet or outlet pipes are introduced into the impoundment through a concrete structure, the seal can be made in the plane of the liner. A special liner-to-concrete adhesive system is suggested that is designed for each liner material. Anchor bolts embedded in the concrete and batten strips of stainless steel should be used to secure the liner to the concrete. Mastic should be used around the edges of the liner material to effect a complete seal.

Typically, specialized features such as pipe boots or shrouds are fabricated at the manufacturing facility to design specifications, although they can sometimes be prepared in the field by experienced personnel. Where reinforced membrane liners are being installed, manufacturers sometimes recommend that boots be constructed of unreinforced liner of the same type as that being installed. This allows the slightly undersized boot to be stretched over the appurtenance to assure good physical contact and allows some expandability in case the adjacent liner stretches due to settling. The boot is slipped over the pipe after the main piece of the liner has been cut and fitted around the base of the pipe. The proper adhesive is applied between the pipe and boot and a stainless steel band is placed around the boot where the adhesive has been applied between the pipe and boot. The base of the boot is seamed to the main part of the liner using the same adhesive system and methods used to make the field seams. Boots should be

checked prior to installation to ensure that the angle of intersection with the base is consistent with the angle created between the pipe and subgrade.

It is important to assure that no "bridging" occurs in the liner material where angles are formed by the subgrade. Bridging is the condition that exists when the liner extends from one side of an angle to the other, leaving a void beneath the liner at the apex of the angle. Bridging occurs most often at penetrations and where steep sidewalls meet the bottom of the impoundment. Installers recommend that particular attention should be directed to keeping the liner in contact with the subgrade at these locations and that it be in a relaxed condition. It is also important to be sure that compaction of the subgrade in these areas meets design specifications to avoid localized stressing of the liner material or seams.

Special considerations must be given to instances where dynamic head is going to be dissipated onto the liner. This would occur, for example, at an inlet structure where water will be flowing into the impoundment. Generally, a splash pad should be constructed by placing one or more additional layers of liner at the point of impact to help absorb energy resulting from the inflow of water. A concrete pad or a filter fabric geotextile also may be used under the liner to ensure further mechanical stability. If water is to be discharged into an impoundment, often the design will specify a sluice-type trough which also can be constructed out of liner material and prevent damage to the main liner resulting from any abrasive material which might be present in the water discharged into the facility.

If gases are expected to accumulate under the liner or if large expanses of the sides of an impoundment will be exposed to high velocity winds, gas vents should be installed. Gas vents should be located just below the berm on the free board area.

If an aeration system is part of the facility design, appropriate precautions should be taken to ensure that the liner surrounding the structure remains in position. This is usually accomplished by using a mooring pad placed on top of the liner for a floating aerator. The mooring pad also prevents mechanical damage to the liner immediately adjacent to the aerator. It is recommended that an additional layer of liner material be placed between the mooring pad and the main part of the liner. When a fixed aerator is used, the liner material may cover the foundation pad and an additional pad can be poured over the liner. Here again, an additional layer of liner material is sandwiched between the pad and liner. Permanent anchors should be placed 10 feet apart in a circle approximately 20 feet from the base of the aerator to prevent the liner material from being lifted from the subgrade.

Quality Assurance/Quality Control--

A well planned and implemented quality assurance/quality control (QA/QC) program begins during design and proceeds through installation and operation of a landfill or surface impoundment. With respect to installation of liner systems, a QA/QC program implies those steps or activities needed to assure that the liner is installed according to design and manufacturer

recommendations. A QA/QC program will provide the owner with increased confidence that the liner will function as intended.

The type and implementation of QA/QC programs vary greatly within the industry. There is no industry-wide standard practice or recommendations regarding QA/QC. Several designers and manufacturers recommend the following items be incorporated into a QA/QC program:

- A checklist to assure all facility requirements have been met.

- A specific plan to be used during construction for observation, inspection and testing of subgrade, liner material, factory and field seam quality, installation workmanship, and assurance that the design is followed. Daily records must be maintained of all aspects of the work of all tests performed on the subgrade and liner. For example, air lance seam testing with periodic field seam tensile testing.

- Throughout construction, a qualified auditor responsible to the operator/owner should review and monitor output. This is an ongoing check on the contractor/installer. It generates confidence that the work was indeed done as planned. Changes to planned procedures must be justified immediately and subsequently documented. This can avoid serious conflicts between the owner and design/installation team after the job is completed.

Quality control/inspection programs can result in more effective installations by assuring planned review and tracking of all installation activities.

There are three major specific areas of quality control concern in a polymer membrane lined facility. They are the subgrade, membrane seams, and sealing of penetrations through the liner.

A knowledgable representative of the primary facility operator, or representative of the ultimate owner of a lined facility, should be assigned as the quality control agent or engineer on liner installations. The agent will be required to assure that the contractual obligations of the installating contractor(s) are met and that the installation specifications are fully met. Personnel reviewing the design or performing quality control functions for a liner installation should be familiar with the liner manufacturer's recommendations regarding all facets of the materials' use and installation. This includes everything from the liner's compatibility with the material being stored to recommendations regarding specific adhesive systems and special seaming instructions around penetrations.

Soil Cover Recommendations-

Several manufacturers of membrane liners suggest that a soil cover be placed over the liner after installation is completed. This practice is recommended for two basic reasons. The first reason is to provide a protective barrier against mechanical, weather, and other environmental damage. Ultraviolet light for extended periods can degrade certain polymeric

materials. Most liners made of PVC are especially susceptible to UV light. Generally, PVC manufacturers suggest placing a soil cover over material exposed to sunlight for extended periods (> 6 months). The second reason is to minimize mechanical damage from landfilling operations, wave action, freeze/thaw cycles, vandalism, hail, and wildlife.

Manufacturers of other liner materials do not require a soil cover. Manufacturers and installers of high density polyethylene and CSPE question whether the mechanical protection benefits are worth the cost of a soil cover and the risk of damaging the liner while a cover is placed. Soil covers are normally placed using bulldozers or pan scrapers. Therefore, the placement of the soil covers, themselves, increases the chance of puncture of the polymeric liner, and once covered, punctures cannot be readily detected and repaired with current technology. The only requirements of a cover material are that it must be free of sharp stone and other objects and that it not be incompatible or reactive with any waste that is to be placed on it. The cover material should be stable and resist sloughing from wave action, and not contain large or sharp material which could puncture or damage the lining.

Clay Liners

The use of clay as a liner implies that the clay has been placed at a site to impede the flow of liquid, or that existing native material has been reworked or recompacted to achieve a lower permeability. The U.S. Department of the Interior's Brine Disposal Pond Manual suggests the following regarding construction of compacted earth liners:

- The liner should be compacted in successive horizontal layers not more than six inches thick after compaction.
- Side slope liner thickness ranges from 2 to 3 feet, while floor thickness ranges from 1 to 2 feet.
- Compaction denstiy in place should achieve 95 percent of Proctor laboratory maximum density.
- Compaction densities are best achieved with tamping rollers.
- Weather conditions must be relatively dry during construction to allow the moisture content of the clay to be controlled.

Many state regulatory agencies have recommended clay liner specifications. These should be checked during the design phase of the project.

Sprayed-On Liners

Sprayed-on liners are formed in the field by spraying a liquid onto a support medium or the earth. They are considered flexible membranes in that they will conform to the subgrade surface. The types of materials used include catalytically-blown asphalt, asphalt emulsions, latex rubber compounds, and modified asphalt.

With all types of sprayed-on liners, it is recommended that the subgrade be smooth, free from rough or irregular objects. If this surface cannot be provided, then a sand bedding is recommended.

Blown asphalt liners are installed at temperatures between 200-220°C and applied at the rate of 1.5 gallon/yard^2. Application is by spray bar offset to the side of a truck. Pinholes can be minimized by making three passes at a rate of 0.5 gallon/yard^2. The final product is approximately 0.25 inch thick. An overlap of 1 to 2 feet between sections is recommended. Sand or dirt accumulation on the asphalt between applications must be avoided to prevent pinholes or inadequate bonding.

Asphalt emulsions are often applied onto a support fabric or jute, glass or synthetic fabric, such as a geotextile. The membrane forms after the emulsion breaks and the water evaporates. Several applications are used to avoid pinholes and porosity resulting from entrapped water.

A modified asphalt membrane is installed by spray bar or a hand held sprayer. The asphalt is mixed with an activator and applied to a geotextile fabric mat at ambient temperature. The activator must be maintained at a temperature greater than 60°F. A 50-mil membrane can be obtained by using a fabric mat with a weight of 0.34 ounce/yard^2 and an asphalt application rate of 0.28 gallon/yard^2. During application, the fabric must become completely saturated to produce a satisfactory liner. Application rates up to 10 yard^2/minute can be achieved using approved application equipment. Experienced field supervision is recommended by the manufacturer.

Soil Sealants

Soil sealants reduce the permeability of soil through a variety of mechanisms, including ion exchange and porosity reduction. Sealants currently used for reducing permeabilities in soil liners at landfills and surface impoundments are primarily polymeric enhanced bentonite sealants which swell when wetted. One product contains linear and cross-linked polymers. The linear polymer sorbs to the soil to produce a flexible network. The cross-linked polymers flow into the soil pores and reduce porosity and permeability. The matrix of bentonite clay is primarily the sodium variety clay mineral, montmorillonite. This mineral swells up to ten times its dry volume when wetted. Sodium montmorillonitic bentonites are found primarily in South Dakota and Wyoming. Reductions in permeability down to 10^{-8}cm/sec are achievable according to the manufacturers of polymer bentonite sealants.

The major manufacturers of polymer modified bentonite soil sealants recommend dry blending with the soil for construction of a soil liner. The appropriate sealant application rate to achieve the desired permeability is established in the laboratory. The sealant is then applied to the soil at the predetermined rate. Typical application rates range between one and two pounds per square foot of area. Application is accomplished using mechanical or pneumatic spreaders such as those used to spread lime or fertilizer. The sealant is blended with the top four to eight inches of soil using an agricultural disc, rototiller, or spring harrow. Equipment

selection depends upon soil type and equipment availability. The rototiller appears to provide the highest level of blending.

After blending, the mixture is compacted. Recommended compaction densities range from 85 to 95 percent modified proctor density. Water may have to be added to the soil/sealant blend to achieve the desired density. In place samples or prepared soils may be taken and tested for specified permeability. After the proper blend has been achieved, the mixture is saturated with fresh water to effect the swelling of the clay mineral montmorillonite.

Admix Materials

Several admixed (formed in place) liners have been used in the construction of fluid impoundments and landfills. The most common is hydraulic asphaltic concrete for this application. The following discussion relates to this type of admix liner.

The Asphalt Institute has several technical publications which provide useful information regarding the intallation of asphaltic concrete liners for fluid impoundments or landfills. Publication MS-12, Asphalt in Hydraulics, indicates asphaltic concrete used for liners should normally contain a higher percentage of mineral filler and asphalt cement than standard paving asphaltic concrete. This produces a liner having more void spaces filled and therefore, a greater density. This property decreases the liner permeability.

For proper placement of asphatlic concrete liners, subgrades must be smooth and flat. Normally, a smooth flat surface is produced by using a steel vibratory roller or similar equipment after the desired grading is achieved. A stable subgrade is critical to a successful installation since the asphaltic concrete liner will not support significant loads by itself. The top six inches of subgrade should be compacted to 95 percent of maximum Proctor density. A herbicide should be applied if the potential exists for weed growth through the liner. Next, hot liquid asphalt is applied to the subgrade and allowed to cure. The asphaltic concrete is applied using standard paving machines if the area to be paved is large. These machines normally are capable of spreading courses 10 to 15 feet wide. If the area is small, such as a patch, manual labor is utilized in lieu of a paving machine. The applied asphaltic concrete course should be smooth and have a consistent minimum thickness of two inches. Where greater thickness is required, a second course is recommended over the first with staggered construction joints. Staggered joints enhance tightness, impermeability, and strength. Application and placement of any asphaltic concrete liner should be planned to avoid cold joints. If this is not possible, cold joints should be heated prior to the forming of a new joint.

Compaction is required immediately after placement. Light steel-wheel rollers, or rubber-tired rollers can be used for compaction. Self-propelled rollers are suitable for relatively flat surfaces. On side slopes, towed rollers may be required to achieve compaction. After compaction, a hot

asphalt surface sealer is recommended. This protects the asphaltic concrete surface from degradation and penetration by the stored fluids.

FIELD OBSERVATIONS

Membrane Liners

Fourteen membrane liner construction sites were visited during the project period. The type of facility and type of liner for each site is shown in Table 6. Observations made at these sites regarding each of the major elements of installation procedures are discussed in the following sections.

TABLE 6. MEMBRANE LINER CONSTRUCTION SITES VISITED DURING PROJECT PERIOD

Facility Type	Liner Type
Mine Tailings Storage	PVC/CSPE
Municipal Landfill	PVC
Evaporation Pond	HDPE
Potable Water Storage	CSPE
Brine Storage	CPE
Tailings Storage	CSPE
Potable Water Storage	CSPE
Evaporation Pond	CPE
Hazardous Waste Landfill	CSPE/Clay
Spill Containment	Neoprene®
Industrial Waste Storage	EPDM
Municipal Landfill Cover	PVC
Municipal Wastewater Storage	CSPE
Spill Containment	PVC

Subgrade Considerations--

Compaction densities were at least 90 percent of Proctor for all but one installation listed in Table 6 where a liner was placed over a landfill. Surface textures were consistent at all but one facility.

The installation contractor at the second facility, a municipal landfill, covered sharp sandstone subgrade with a geofabric before liner placement. The fabric served as a substitute for a sand bed.

Three facilities incorporated a cushioning medium over the native subgrade. At the second facility, 6 in. of sand was placed over a rough sandstone. At the fourth and tenth facility one foot of sand was placed over concrete subgrades prior to liner placement. Liner installation was performed at three sites where the subgrade was saturated. Standing water was present at various places over the subgrade. However, the liner was not installed over water at any of these sites. Soil sterilization was accomplished at two of the 12 sites with earthen subgrades. At both of these locations, vegetation had existed prior to excavation. The subgrade

at the eighth installation was not sterilized and subsequent to liner placement, salt grass grew through the liner, necessitating significant liner repair.

Figure 1 shows typical subgrade compaction equipment at work. Figure 2 shows equipment used to smooth an earthen subgrade. Figure 3 shows various surface textures of subgrades. Figure 4 shows a worker applying an herbicide to a finished subgrade and the result that can occur if this is not done. A watering trailer used to prepare soil for compaction is shown in Figure 5.

Onsite Storage of Material--

Onsite storage of liner material was observed at eight of the fourteen sites visited. All of these sites were being constructed within a secured area. Therefore, storage of material at the impoundment site was considered to be in a secure area. Protection from direct sunlight was provided at two sites. Field crew members at the remaining sites indicated protection was not needed due to either the short time between delivery of the material and placement, or existing ambient temperatures did not warrant protection. Figure 6 shows panels of rolled and accordion folded liner material stored at the site. Figure 7 shows rolls of high density polyethylene (HDPE) rolled on steel drums.

Installation Equipment--

Figure 8 shows one manufacturer's automatic welder used to install high density polyethylene. This is a high temperature operation, and requires 220 volt power onsite. A front end loader was used to lift the rolls of material, weighing approximately 5000 pounds.

Figure 9 shows a field seaming crew member about to roll a seam that has just been prepared with a solvent. Figure 10 shows sandbags that are placed around the large sheets or panels of material to prevent wind damage. Figure 11 shows heat guns often used to preheat the surface of the membrane, providing a better seam.

Manpower Requirements--

Field personnel observed at the study sites ranged in number from five to thirty. Generally speaking the larger the site, the larger was the numbers of field personnel. At all but one location, crew foreman representing the installer were on site to direct installation. Workers were hired locally as required. The exception was a high density polyethylene installation. All crew members were employees of the manufacturer and installer.

Liner Placement Procedures--

Figure 12 shows panels of membrane material being unfolded and moved into proper position. Unfolding is normally begun at the anchor trench around the perimeter of the facility. Once the panel is unfolded, it is pulled across the subgrade by the field crew, as shown. Workman grip the panel using dowels which are rolled from the edge of the panel toward the center enough to provide a handle. The edge of the panel is raised and flipped to pump air under the liner. This allows the liner to be pulled into position without damage. This prevents stretching of the materials. Windy conditions may cause serious difficulties for field crews.

Figure 1. Subgrade compaction with a vibratory steel wheel roller.

Figure 2. Equipment used to fine finish the subgrade.

Figure 3. Rough unfinished subgrades prior to surface rolling.

Figure 4. Application of an herbicide to prevent vegetation growth, as shown in bottom photo.

Figure 5. A watering vehicle used to prepare soil for compaction.

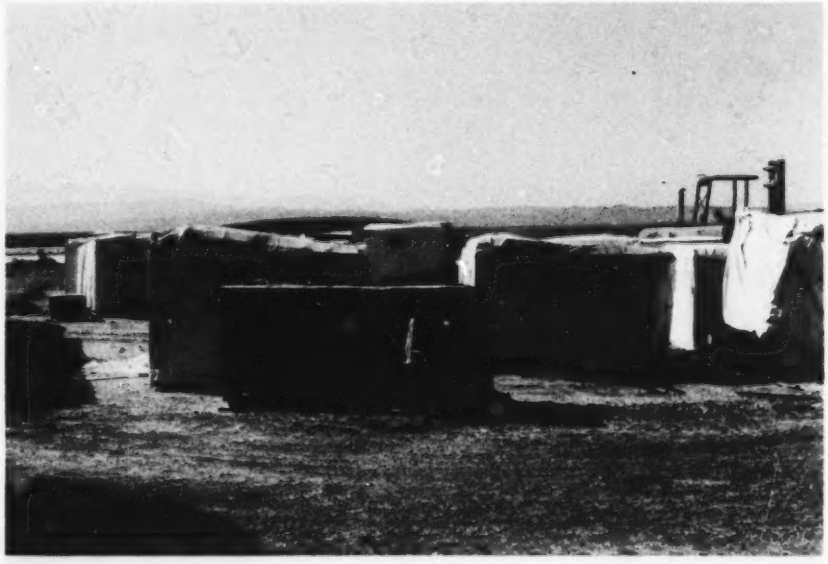

Figure 6. Liner material stored at the construction site.

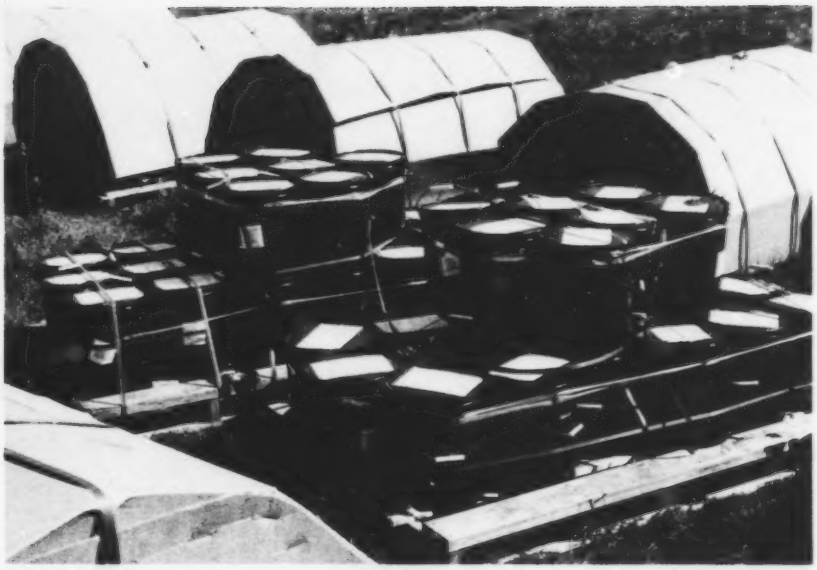

Figure 6 (Continued). Liner material stored at the construction site.

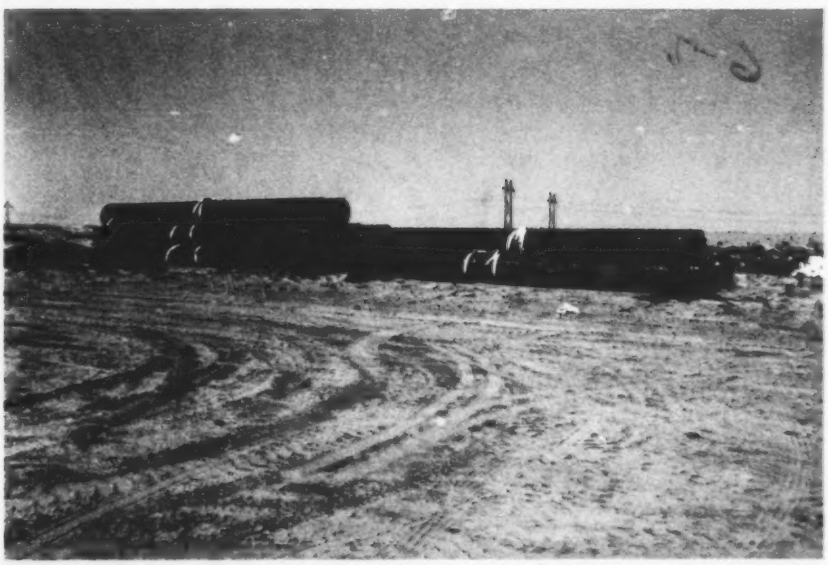

Figure 7. HDPE rolls stored at the site.

Figure 8. Automatic welding machine and control panel for HDPE liner material.

Figure 9. A workman preparing to roll a solvent bonded seam.

Figure 10. Sandbags placed at the edges of the material to prevent damage.

Figure 11. Use of heat guns to heat the surface of the liner.

Figure 12. Unfolding sheets or panels and positioning them for field seaming.

Once the panel is unfolded, the crew positions it properly, providing the necessary slack and overlap of seams. Sandbags are placed along the edges to prevent wind damage, as was shown in Figure 10. At this point, field seaming crews begin joining the panels together. Table 7 presents a summary of liner placement activities observed at the sites visited during the study.

Field Seaming Procedures--

During liner placement, the panels must be positioned so the recommended seam overlap will be maintained along the entire edge of the pond. Generally, overlaps were 2 to 12 inches, depending on the material. After correct overlap is achieved, field seaming crews begin inspecting the liner surface to be seamed together. Foreign material, such as dirt, or moisture is wiped off with rags or brooms. A surface oxidation or "cure" has to be removed from certain types of membranes. This is accomplished using a solvent such as trichloroethylene or methyl ethyl ketone. Workers normally wear protective gloves whenever working with these solvents. After removing the surface oxidation, a liberal quanity of solvent is applied. The material is allowed to soften at the surface. Solvent is applied to both surfaces to be seamed together. The two surfaces are pressed together with rollers. A board is often placed under the seam to provide a firm surface for rolling the seam. This procedure is typical for those materials seamed with a solvent. PVC, CSPE and CPE are commonly field seamed with solvents. Figure 13 shows a worker applying a solvent to CPE. The overlap was 8 inches. Figure 14 shows the seam being rolled together using a hand-held roller.

Contact type adhesives are used with vulcanized liner materials, such as EPDM, To seam these materials, the surface is prepared with a petroleum distillate, such as fuel oil. Then a contact adhesive is applied to both surfaces as shown in Figure 15. When a tacky surface is produced, the two are folded over and pressure is applied. Often, a caulking compound is applied at the edge to complete the seam. A cap strip is then applied over the seam, shown in Figure 16.

High density polyethylene liners are bonded together by welding. Equipment to perform welding in the field was shown in Figure 8. The automatic machine applies a ribbon of hot HDPE approximately two inches wide between the two liner surfaces which have been preheated. Pressure is applied to the seam at the rear of the unit. The entire machine moves under its own power at a rate set by the worker. Power is supplied by an onsite generator set. HDPE pellets are loaded into the machine, melted, and extruded out a die as the ribbon previously mentioned. This procedure requires a skilled operator to achieve a successful weld.

Solvent seaming produces a physical bonding between materials by chemically dissolving the surface layers of the material. Heat seaming simply melts the surface layer of the material to allow the bond to be achieved. A variety of heating devices are used to heat seam membrane liners. Liester guns air heat the material. Direct contact heating elements are also used. Heat seaming is very difficult and does not necessarily provide a superior field seam compared to other available methods. Heat seaming was observed at only one site visited during this study.

TABLE 7. SUMMARY OF LINER PLACEMENT ACTIVITIES OBSERVED AT 14 LINED FACILITIES

Facility Type	Mode of On-Site Material Storage	Air Temperature During Installation (°F)	Spotting Techniques	Overlap Width (in.)	Seam Width (in.)	Sealing System	Method to Seal Penetration	Gas Vents	Mode of Final Securing of Liner
Tailings Storage	Cardboard Boxes and Pallet	80-100	Ten-Twelve Man/Panel Machine Assisted	6	3	Solvent	Not Observed	Yes	Vertical Slit Anchor Trench Filled with Soil
Municipal Landfill	Unprotected on Pallets	35-50	4 Man/Panel	2-6	1-2	Heat Gun	Not Applicable	No	Anchor Trench Filled with Soil
Evaporation Pond	Unprotected Rolls	60-80 (Night)	Mechanized Due to Panel	6	1	Heat Gun	Not Observed	No	Half Anchor Trench Filled with Soil
Potable Water Storage	Cardboard Boxes on Pallet	50-65	8 Man/Panel	12	2-4	Solvent	Mastic with Mechanical Seal	No	Batten Strips to Concrete
Brine Storage	Cardboard Boxes on Pallet	80-90	Four-Eight Man/Panel Manual	6	2	Solvent	Mastic with Overlying Weight	No	Vertical Slit Anchor Trench Filled with Soil
Tailings Storage	Cardboard Boxes and Pallet	80-95	Not Observed	6	2	Solvent	Not Observed	No	Vertical Slit Anchor Trench Filled with Soil
Potable Water Storage Concrete	Cardboard Boxes and Pallet	60-95	Six-Eight Man/Panel	4	2	Solvent	Not Observed	No	Vertical Slit Anchor Trench Filled with Concrete

TABLE 7 (Continued).

Facility Type	Mode of On-Site Material Storage	Air Temperature During Installation (°F)	Spotting Techniques	Overlap Width (in.)	Seam Width (in.)	Sealing System	Method to Seal Penetration	Gas Vents	Mode of Final Securing of Liner
Evaporation Pond	Reflective Material Over Cardboard Boxes	70-950	Six-Eight Man/Panel	4-6	2	Adhesive	Adhesive and Tensioned Band	No	Half Anchor Trench Filled with Soil
Hazardous Material Landfill	Unprotected on Pallets	60-80	Not Observed	4-6	4	Solvent	Not Applicable	No	Half Anchor Trench Filled with Soil
Spill Containment	Cardboard Boxes and Pallet	60-80	Four-Six Man/Panel	4	2	Heat Gun	Adhesion, Mastic Tempered Band	No	Batten Strips to Concrete
Industrial Waste Storage	Burlap Wrapped Rolls	60-70	Six-Eight Man/Panel Machine Assisted	6	4	Adhesive and Lap Sealant	Not Observed	No	Half Anchor Trench Filled with Soil
Municipal Landfill Cover	Unprotected on Palletts	40-60	Six Man/ Panel	2-6	1-2	Solvent with Heat Gun	Solvent with Mechanical Seal	Yes	Half Anchor Trench Filled with Soil
Municipal Wastewater Storage	Cardboard Boxes and Pallet	70-85	Four-Six Man/Panel	4	2	Heat Gun	Not Observed	Yes	Vertical Slit Anchor Trench Filled with Soil
Spill Containment	Unknown	90-95	Three Man/Panel	6	4-6	Adhesive and Lap Sealant	Adhesive with Mechanical Seal	No	Half Anchor Trench Filled with Soil

Figure 13. Solvent applied to a CPE seam.

Figure 14. A seam rolled together by hand.

Figure 15. Contact adhesive applied to an EPDM liner.

Figure 16. A cap strip applied over an EPDM seam.

Problems with an excess of material at field seams were observed at several sites. Since the length of the panels are often hundreds of feet in length, it becomes difficult to consistently achieve overalp seams with no excess material. When slack or excess material occurs, it must be removed or folded over to achieve a good field seam. Figure 17 shows this procedure observed at one site. A heat gun was used to soften the material. A solvent adhesive was applied to both surfaces and the flap folded over on itself. A patch of material is then bonded over the fold. This procedure occured many times at this installation as well as at others.

Adverse weather conditions for field seaming were observed at several sites. Temperatures below 60°F prevented one installer from completing adequate field seams using a solvent adhesive. Heat was employed to finish the seaming process. Another installer had difficulty with blowing sand accumulating on liner surfaces before an adequate seam could be produced. Excessive heat, causing expansion of high density polyethylene, forced the welding of material to be accomplished at night when material temperatures were reduced.

Figure 17. Common sequence used to remove a wrinkle.

Figure 17 (Continued). Common sequence used to remove a wrinkle.

Sealing Around Structures/Penetrations--

Various approaches to bonding liner material to concrete, metal, or plastic structures were observed at the majority of sites visited. Generally speaking where the structures were the same material as the liner, bonding appeared to be a simpler task requiring fewer steps. High density polyethlyene and PVC liners can be bonded directly to pipes made of the same material. However, basic resins used to make these materials may have different thermoexpansion characteristics. Therefore, the installer should be sure they can be bonded together prior to installation.

The design of most installations visited included some type of structure that penetrated the liner system. These structures included inlet/outlet pipes, concrete support piers, drain flanges, gas vents, and concrete emergency overflow abutments. For those cases where liner material and structure material were incompatible, several approaches to sealing were observed. For sealing liner material to concrete, a combination of a mechanical and mastic system was used at one site. Anchor bolts were placed into the concrete to secure steel strips. The steel strips were placed over the liner. Between the liner and the concrete, a mastic was applied to make a tight seal. A mastic recommended by the liner manufacturer that is compatible with the membrane and the waste was chosen for this purpose. A mastic was not used if the seal would be exposed to the fluid stored in the facility. Figure 18 shows the use of steel strips to secure a CPE liner to a concrete support pier. The steel was bolted to the pier footing. A boot was then placed over the concrete pier.

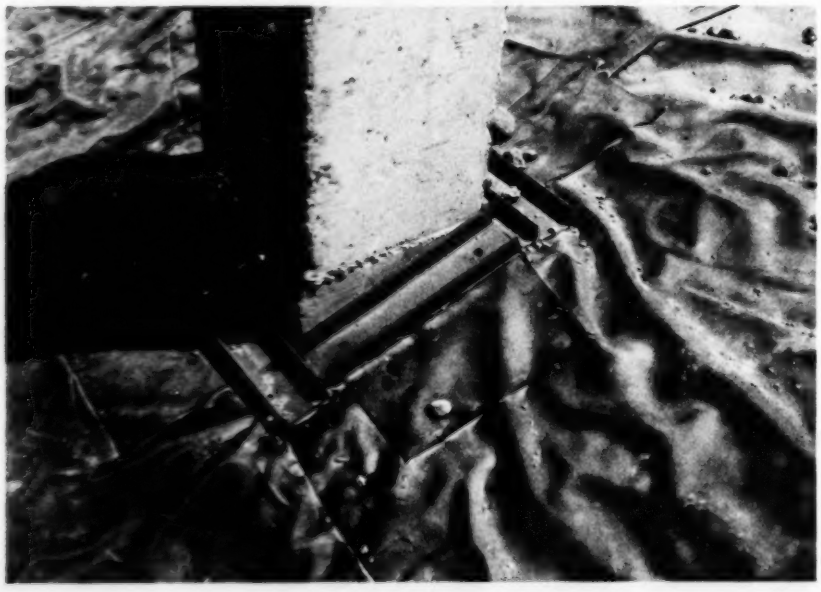

Figure 18. Steel strips bolted to concrete to secure the liner.

Incompatible liner materials and structural materials are joined using a combination of mechanical devices and boots made of the liner material. At one location, an inlet pipe made of fiberglass was isolated by the use of a boot constructed in the field with a mechanical clamp sealing off the pipe to fluid movement (Figure 19). The boot was bonded to the side slope of the impoundment to complete the seal. For a large number of penetrations, the installer generally will work with a fabricator to construct boots in the factory rather than in the field. Figure 20 shows a schematic of the type of boot described above.

All polymeric liners are anchored at the berm or top of a landfill or surface impoundment. Normally, this is accomplished as shown in Figure 21. The edge of the liner is placed in a trench typically one foot wide and one foot deep. A backfill of earth or concrete secures the edge in the trench. Figure 22 shows a typical anchor trench design.

Quality Assurance/Quality Control--

With respect to membrane liner system installation, quality assurance/quality control (QA/QC) activities should be developed to increase the confidence that the liner system was installed as specified. The more extensive the QA/QC program, the higher degree of confidence the owner would likely have that the system will function as intended.

Observed activities in the field which were intended to be QA/QC type activities ranged from sampling field and factory seams from every panel placed to simply visual inspection of field seams. At two sites, independent third party contractors provided checks of all installation activities and prepared a summary of compliance with installation plans and procedures. These contractors were onsite during the entire installation period. At one of these sites, samples of each seam were taken and sent to a laboratory for testing. Laboratory results were reviewed by the QA/QC contractor. If the samples did not meet minimum requirements, the seam was remade. The decision to remake the seam was not subject to interpretation. If problems were identified, resolution was the responsibility of the QA/QC contractor. At both of these sites, the seam testing performed was destructive testing in the sense that the sample was cut from the field seam. This method of testing meant that for each field seam sample taken, a patch was installed in the liner system. Both QA/QC inspectors believed the benefits gained from sample testing outweighed the drawbacks of having to patch an equal number of cuts in the liner.

Table 8 presents a summary of various QA/QC elements observed at the sites visited during this project. Personnel were assigned and wholly dedicated to the job of inspecting the quality of work at seven sites. As previosuly indicated, the owners of two sites contracted third parties to conduct QA/QC onsite. At the five other sites, QA/QC inspection was performed by either the installer's personnel or the manufacturer's personnel. The installation field chief provided QA/QC at the other seven sites.

Subgrade inspection was performed at every site, since this is critical to the success of a liner system. Testing to determine adherence to density requirements was performed at eight sites. Two of the remaining six involved

Figure 19. A boot constructed around an overflow pipe.

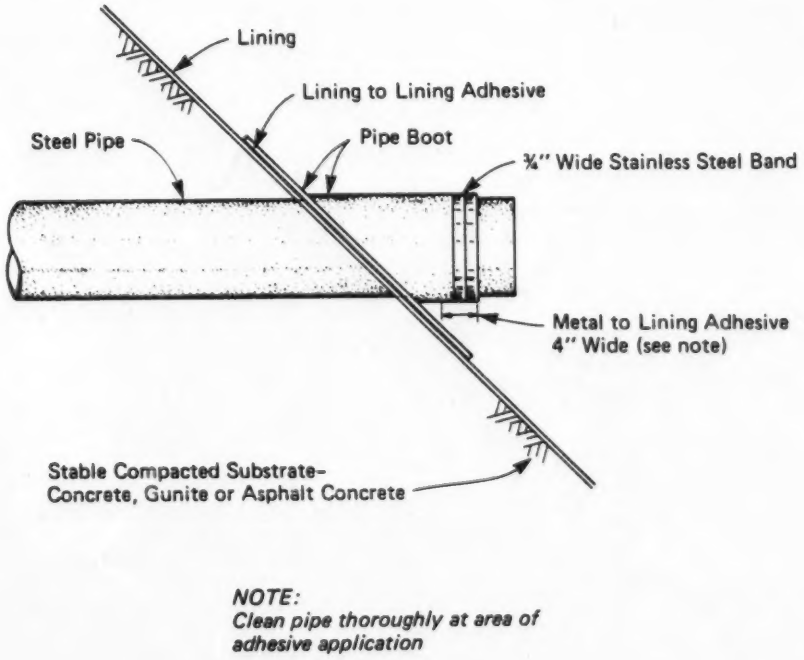

Figure 20. Detail of boot construction.

Figure 21. Typical anchor trenches filled with earth or concrete.

TABLE 8. SUMMARY OF FIELD QUALITY ASSURANCE OBSERVED AT 14 LINED FACILITIES

Facility Type	Wholly Dedicated Inspection Personnel	Subgrade Inspection	Subgrade Testing	Liner Material Exam	Field Seam Examination			
					Visual Exam	Physical Testing		
						Qualitative	Quantitative	
							Non-Destructive	Destructive
Tailings Storage	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
Municipal Landfill	Yes	Yes	No	Yes	Yes	Yes	No	Yes
Evaporation Pond	No	Yes	Yes	Yes	Yes	Yes	Yes	No
Potable Water Storage	No	Yes	No	Yes	Yes	Yes	No	No
Brine Storage	No	Yes	Yes	Yes	Yes	Yes	No	No
Tailings Storage	No	Yes	Yes	Yes	Yes	Yes	No	No
Potable Water Storage	Yes	Yes	Yes	Yes	Yes	Yes	No	No
Evaporation Pond	Yes	Yes	Yes	Yes	Yes	Yes	No	No
Hazardous Materials Landfill	No	Yes	Not Known	Yes	Yes	Yes	No	No
Spill Containment	Yes	Yes	No	Yes	Yes	Yes	No	No
Industrial Waste Storage	Yes	Yes	Yes	Yes	Yes	Yes	No	No
Municipal Landfill Cover	Yes	Yes	No	Yes	Yes	Yes	No	No
Municipal Wastewater Storage	No	Yes	Yes	Yes	Yes	Yes	Yes	No
Spill Containment	No	Yes	No	Yes	Yes	No	No	No

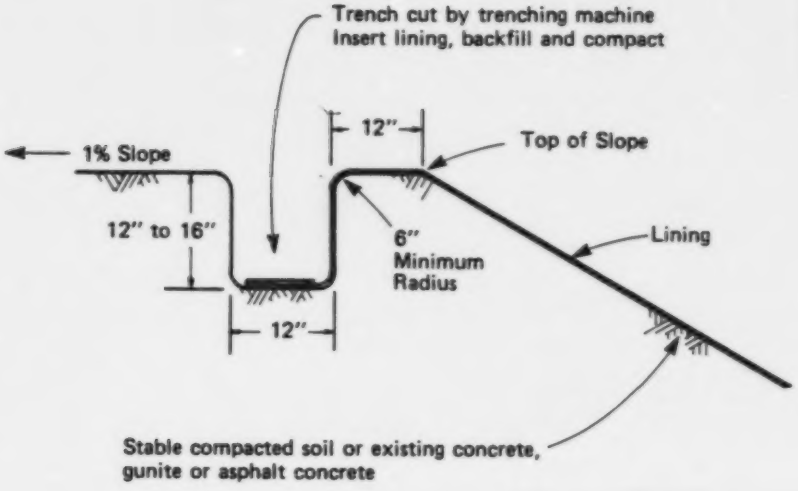

Figure 22. Detail of a typical anchor trench.

concrete subgrades, and were not tested for that reason. No testing was performed at the balance of sites.

The quality of the liner material in terms of visual appearance was determined at every site at the time the material was placed onto the subgrade. Quantitative, non-destructive testing was performed at two sites. Methods used were ultra-sonic testing and tensile testing of field seams. Destructive testing of seam samples was performed at two sites which were previously discussed.

Soil Covers--

Soil covers were installed over the liner systems at seven of the fourteen sites. Three of these sites specified PVC liner material which requires a soil cover for ultraviolet light protection. The remaining four sites installed covers for protection against heat or mechanical damage. Equipment to accomplish this task included bulldozers, pan scrapers, and front end loaders. Figure 23 shows soil being deposited over the liner at two sites. Soil covers were not installed at seven sites. Manufacturers of these materials did not require soil covers as a condition of material warranty.

Clay Liners

One clay liner installation was visited during the project. Clay deposits suitable for lining a waste fluid impoundment were hauled approximately two miles, deposited on the subgrade, and reworked with water to approximately 90% of Proctor density. A bulldozer was used to apply and compact the clay. The thickness of the liner was approximately 18 inches after compaction.

Figure 23. A soil cover being placed at two sites.

Figure 24 shows the clay liner in the foreground. Owners of this facility had previous experience with clay liners. Representatives were on site throughout construction to assure design specifications were achieved. Periodic soil moisture measurements were taken.

Sprayed-On Liners

One site visited during the study was a test evaporation pond to be lined with a urethane modified asphalt liner system. The system is comprised of a polypropylene geotextile coated with the urethane asphalt material. Loose desertic soil with high permeability was present at the site. A 6-inch overlap was maintained along all joints. Four-inch staples were used to temporarily secure the mat to the soil until the asphalt could be applied. The mat was extended over the top of the side slopes into an anchor trench 1-foot deep around the perimeter of the impoundment.

To prepare the urethane asphalt for spray application, a premix was combined with an activator at a volume ratio recommended by the manufacturer. Mixing was accomplished in 5-gallon buckets. The mixture was applied using a specialized spray application unit. This unit attached to a 5-1/2 gallon container. Figure 25 shows the fabric mat positioned over the subgrade and the spray unit. A compressor/generator unit was used to provide necessary power for the spray unit. The asphalt was then applied using the hand held spray gun, shown in Figure 26. Sufficient asphalt was applied to achieve saturation of the fabric mat. The installer visually determined when saturation had been achieved. One coat was applied at the rate of 2 gallons per minute, covering about 8 square yards per minute. This application rate produced the desired membrane thickness of 50 mil. Note in Figure 27 that the horizontal seam on the fabric mat behind the applicator has been pre-soaked with the asphalt material. This was done for all fabric seams to assure penetration of material at the critical seam overlaps. In addition, the fabric mat extending into the anchor trenches was coated with asphalt. The installer recommends that the membrane be allowed to cure for 24 hours before being put into service.

Soil Sealant Liners

Four bentonite soil sealant liner installations were visited. The largest site is a 42-acre wastewater storage impoundment. A Wyoming bentonite clay modified with a cross-linked polymer was selected as the soil sealant. The native soil is a glacial silt having an unacceptable permeability for the intended use of the impoundment.

The modified bentonite soil sealant was applied pneumatically by using two air bottle transport trucks equipped with hardware specifically designed for this application. The trucks each carried an air compressor, two storage tanks and associated hardware. Two important additions were a 6-foot wide material distribution boot and an outrigger. These are shown in Figure 28. The boot was attached to the rear of the truck. Soil sealant was forced out through the top of the boot. Internal veins running from the inlet to the bottom allowed an even distribution of material. The bottom skirt helped minimize the loss of material during application. The outrigger allowed

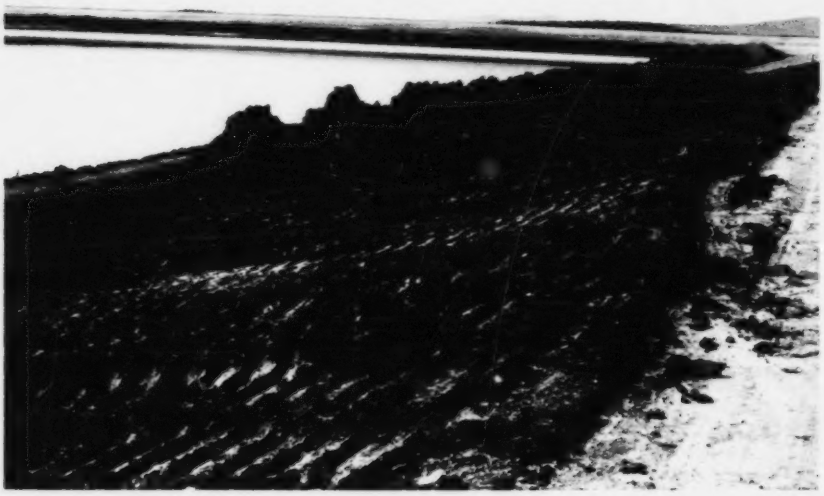

Figure 24. A clay liner being constructed over existing subgrade.

Figure 25. A fabric mat and hand-held spray unit for construction of a sprayed-on membrane liner.

Figure 26. Asphalt being applied to the fabric mat with a hand-held spray gun.

Figure 27. A workman applying excess asphalt to the fabric overlap.

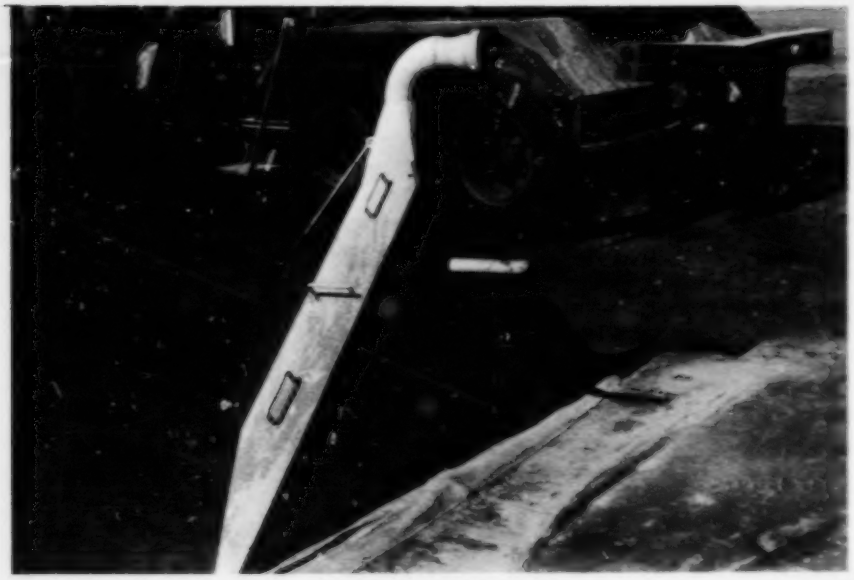

Figure 28. A bentonite distributor and outrigger on the side of the truck.

the operator immediate and safe access to the material control valves on the side of the truck.

Laboratory tests indicated the desired application rate of soil sealant to be 34 tons/acre or 1.6 pounds/square foot. The required flow rate of soil sealant from the truck as well as the rate of travel were established. Prior to initiating application of the sealant, distance markers were set every 100 feet along the toe of the dike. These markers helped the application crew determine the rate of forward movement of the truck. A strict control of the forward rate of travel was necessary to establish the proper application rate of sealant.

As soon as the marker stakes were set, the application crew began spreading the bentonite, as shown in Figure 29. The bentonite can be seen to the right of the truck. This operation requires at least two people, a driver and a person to control the application of sealant. To allow continuous spreading during daylight hours, two trucks were utilized. While one truck was spreading the sealant, the second truck was being loaded with sealant stored in six 25-ton capacity silos located on site. The storage capacity in the silos equaled the quantity of material which could be applied in one day by two trucks.

A tarp was used by the on-site quality control engineer to assure the proper quantity of sealant was being applied. The tarp was weighed after the truck passed over it to determine the quantity of sealant material applied in one pass. This test was performed periodically throughout the application procedure.

Figure 29. An oil field bottle truck fitted with the distributor and applying bentonite to the subgrade.

The large agricultural disc shown in Figure 30 followed the application crew. Approximately eight passes in a crisscross pattern were made to blend the sealant with the soil. The decision as to whether adequate blending had been achieved was made by the application foreman and the on-site technical staff representing the owner of the facility. Adequate blending is necessary for the sealant to reduce permeability to the desired level. The crisscross pattern helped break up clods. Figure 31 shows an overview of the discing activity. Freshly applied bentonite can be seen to the left of the disc. The scraper in the foreground is reworking the toe of the embankment to achieve a suitable final grade.

On the second day of application, the installation contractor located an 8 foot wide rototiller. This unit was used to complete the blending for the remaining 39 acres. It performed better than the disc, producing a more uniform mixture of soil and bentonite.

Soil sealant was applied to the side slopes by mounting the spreader boot on the blade of a bulldozer. The bulldozer traveled the side slopes horizontally while tethered to the sealant supply truck by a hose. The supply truck was driven around the top of the dike during application on the upper half of the slope, and around the bottom during application on the lower half of the slope.

Upon completion of the soil and sealant blending operation, water was added to the soil on the floor of the impoundment in sufficient quantity to allow compaction to 95 percent of maximum Proctor density. Sufficient

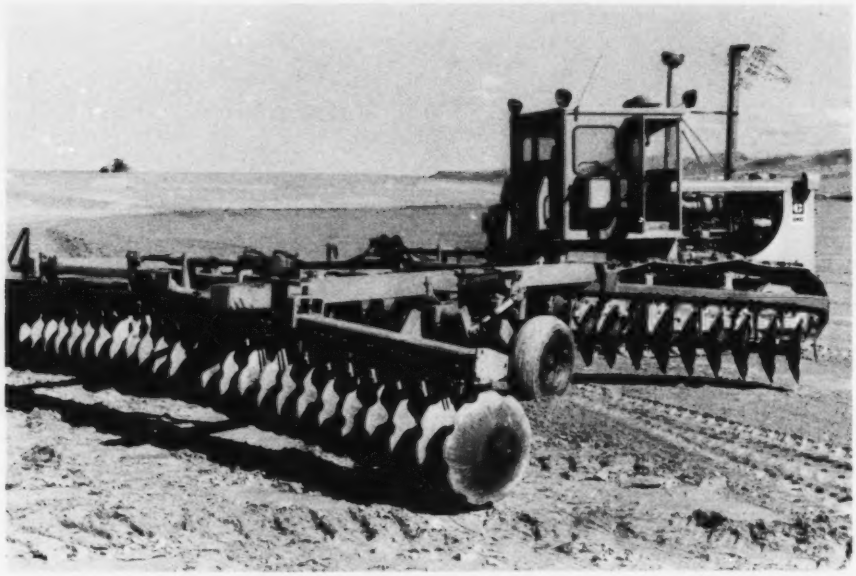

Figure 30. An agricultural disc used to blend bentonite with the soil.

Figure 31. An overview of the blending operation.

moisture was present in the soil on the side slopes to allow the desired compaction without additional water. Due to their steepness, the side slopes were compacted with a rubber tired roller which could traverse the existing grade. The level floor was compacted with a steel roller. To protect against erosion, slag was placed along the side slopes after final compaction.

Bentonite application equipment at the other three sites included a farm fertilizer spreader towed behind a tractor, a front-end loader pushing the bentonite over the subgrade, and placing 100-pound bags of bentonite over the earth on 10-foot centers. Blending was accomplished using a rototiller, a standard agricultural disc and a small spring harrow.

Asphaltic Concrete Liners

One asphaltic concrete liner installation was included in the study. This site is a municipal landfill begun approximately 5 years ago. Presently, the landfill covers 20 acres with an average compacted fill depth of 100 feet. The site is situated in a ravine. Construction was initiated at the upper end of the ravine and is progressing down gradient. Future plans call for the filling of the entire ravine, resulting in a fill covering 170 acres.

The liner at this site consists of 2 inches of road grade asphalt applied using a standard paving machine, as shown in Figure 32. The steel wheel roller was used to compact the asphalt to the desired density immediately after application.

Figure 32. An asphaltic concrete liner being applied with a road paving machine.

After the surface cooled, a seal coat was hydraulically applied. The seal coat is intended to protect the asphalt from potential degradation which might occur as a result of exposure to leachate. An apshalt curb was constructed at the edge of the liner to direct leachate to a perforated PVC pipe located inside the curb upon the normal asphalt surface. The PVC leachate collection pipes from each 5-acre section of asphalt liner are linked together via a manifold system. As new liner is added, the required new piping is connected to the manifold system.

COMPARISON OF INDUSTRY SUGGESTED PRACTICES AND FIELD OBSERVATIONS

Liner industry recommendations and field observations are compared in the following sections for the five liner types included in the study. Comparisons were based upon field observations made during visits to construction sites and those installation practices suggested by the liner industry. The purpose of this comparison is to identify those aspects of liner installation activities found at sites visited during this study that do not appear to follow industry suggestions or were neglected. It is not the intent of this comparison to judge whether observed practices were right or wrong, nor to imply that the liner system will succeed or fail in service.

Membrane Liners

Field observations made at fourteen flexible membrane liner construction sites indicate installers generally follow applicable industry recommendations. For all sites visited, considerable effort had been made during the liner design phase in attempting to anticipate installation problems and develop solutions. Crew experience varied considerably. In one case only the foreman had previous installation experience while in other cases the entire crew had previous installation experience. The extent of experienced personnel at a given project may have been influenced by the installation company, owner policy, or the magnitude or complexity of the job. In all cases, there was either an experienced installation crew chief on site or a technical advisor representing the manufacturer or fabricator of the sheet, or roll goods.

The effect of crew experience and/or technical advice provided by extremely knowledgeable parties on the quality of a given liner installation cannot be quantified. However, all industry representatives stress the importance of prior experience in the liner installation phase. Apparently, the presence of at least one experienced, knowledgeable liner installer at a given site will tend to alleviate the severity of installation problems, while elevating the overall "quality" of a given installation. The end result to the "user" may be an acceptable final product with minimum unplanned additional costs due to unforseen problems.

There were three installation activities which at more than one site appeared not to follow industry suggestions. These were as follows: (1) working during marginal/adverse weather; (2) sealing around penetrations; and (3) qualitative and/or quantitative field inspection or laboratory testing of field seams. Each of these is discussed below:

(1) Effects of Marginal/Adverse Weather--At several sites, installers attempted to work under wet or cold conditions. Both excessive precipitation and cool temperatures can adversely effect the quality of a given liner installation. Precipitation during seaming can cause poor adhesion of the seams unless the areas being seamed are kept dry. All manufacturers state that seams must be kept dry during the seaming process. Similarly, cool weather can cause seams to be of a lower quality than seams formed in warmer conditions. Most material manufacturers recommend that seaming cease where ambient temperatures are less than 60°F (15°C). Seams formed under cool conditions may cure improperly, or not bond properly depending on the seaming technique utilized.

Installers often cannot control the time of year liners are installed. Therefore, weather conditions may not always be ideal, i.e., dry and warm, for installing a liner. In addition, contractual agreements often specify a limited time for completion. This may force the installer to work in less than desirable weather conditions, including hot, cold, or wet weather. Some materials expand excessively in hot weather forcing night work in cooler temperatures.

The experienced, competent installer recognizes that these situations may develop and requires adverse weather clauses in a given contract. An inexperienced installer or owner wanting to install a liner himself may work under adverse weather conditions, thus increasing the risk of poor quality seams or inadequate subgrade.

There are ways to mitigate the effects of working in adverse weather, such as using heat guns for seaming in ambient temperatures below 60°F. Heat seaming does not work on all materials, however. The responsible installer who is required to work in less than ideal conditions will take advantage of specialized tools and techniques.

(2) Sealing Around Penetrations--Sealing around penetrations is critical to the integrity of any lined facility. Improperly devised and/or sealed penetrations may leak. Because pipes, columns, footings, etc., which pass through the beam or floor of a facility may exist in many different shapes and forms, specialized sealing applications must be adopted.

Field observations of techniques used to seal liners to structural penetrations suggest that industry recommendations as to the best techniques are not always followed. Sealing penetrations requires proper liner configuration design to fit around the structure; proper adhesive that is compatible with the materials; smooth, clean ring contact surfaces; and usually, a mechanical device of some sort such as a stainless steel clamp.

The industry recommendations may not be followed if the installer is not involved in the selection or has prior approval of the sealing approach specified. At one site visited, the installer did not have input into the liner sealing design around concrete structures. Design of the methods used to send around penetrations should include input from experienced installers. The installers have worked with these problems and their experience should be utilized during design.

(3) Qualitative and/or Quantitative Field or Laboratory Testing/ Inspection of Field Seams--The industry suggests that some form of inspection of field seams be accomplished at each job site. A quantitative test is preferable coupled with qualitative inspection based on rigorous inspection tenets. Improperly or poorly constructed seams can potentially destroy the integrity of a facility resulting in leakage of fluid and potentially significant monetary loss to the owner.

At approximately half of the sites visited during this study, there appeared to be a general lack of attention paid to thorough inspection of completed field seams. Suggested practice by the industry includes visual and often air lance inspection of seams. Design firms have incorporated statistical sampling programs where random samples of field seams are mechanically tested for tensile strength. At least two installers are presently using a non-destructive device to test the tensile strength of field seams. Field seam integrity generally determines the integrity of the entire job. Therefore, it is important that every reasonable, available field seam inspection method be utilized during construction. This will reduce the risk that the liner will fail to perform its intended function.

Clay Liners

A comparison of the construction activities at the clay liner site visited during this study with generally accepted practices indicates reasonable adherence with recommendations. The clay liner was compacted in six-inch lifts to slightly less than the recommended height of two feet. Compaction densities of less than the recommended 95 percent were achieved. Construction occurred during dry weather, allowing control of water content in the clay.

Spray-On Liners

The installation of the sprayed-on liner system observed during the project complied with all applicable industry recommendations. The subgrade was bladed smooth after compaction. A geotextile was secured to the subgrade and anchored in a trench at the top of the berm. A methane-modified asphalt was sprayed over the geotextile until it was saturated. An experienced field crew constructed the liner under supervision of the asphalt manufacturer. Quality control measures recommended by the manufacturer were followed at this site. Measures included inspection of geotextile overlap at seams, and adequate soaking of the fabric with asphalt. Multiple spray passes were made to eliminate pinholes.

Soil Sealant Liners

Installation practices at the four soil sealant (bentonite) liner construction sites varied with respect to application methods and bentonite/ soil blending techniques. Industry recommendations specify the importance of uniform application and complete blending of the bentonite and soil. Application equipment used at three of the four sites appears to produce uniform distribution of bentonite. At the fourth site, bags of bentonite

were placed in a grid on ten foot spacings. This method did not appear to follow the overall industry recommendations for achieving uniform application.

Complete blending of the bentonite and soil was achieved at two sites using agricultural rototillers. Uniform distribution of the bentonite was verified using laboratory inspection and testing methods. A spring harrow and agricultural disc were used at the other two sites. Blending did not appear to be complete, based upon the appearance of the soil. Tests of the soil liner were not conducted to verify blending uniformity.

Asphaltic Concrete Liners

The asphaltic concrete liner installation procedures used at the site followed accepted industry recommendations with one exception. The subgrade was dry, rolled flat and free of debris. A special concrete mix having a higher mineral filler and asphalt cement content was specified. A minimum of two inches was applied using a standard road paving machine. Steel wheel roller compaction was performed after paving. The exception was that hot asphalt was not sprayed on the subgrade before concrete application. The reason for omission of the hot liquid asphalt is not known.

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